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REGIONAL SEISMIC IDENTIFICATION RESEARCH:PROCESSING, TRANSPORTABILITY AND SOURCE MODELS

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ABSTRACT

Our identification research for the past several years has focused on the problem of correctly discriminating small-magnitude explosions from a background of earthquakes, mining tremors, and other events. Small magnitudes lead to an emphasis on regional waveforms. It has been shown that at each test site where earthquake and explosions are in close proximity and recorded at the same station, clear differences in the regional body waves such as the relative high frequency amplitudes of P and S waves can be used to discriminate between event types. However path and source effects can also induce such differences, therefore these must be quantified and accounted for. We have been using a specific technique called Magnitude and Distance Amplitude Correction (MDAC), (Walter and Taylor, 2002) with some success to account for some of these effects.

Here we briefly present highlights from three aspects of our recent work:

1) *Efficient Processing* – In order to calibrate the source and path behavior of a particular region we need to be able to quickly and efficiently measure hundreds to thousands of prior events. We have developed processing software called Regional Body-wave Amplitude Processor (RBAP) that is optimized for quickly selecting data, reviewing seismograms and making amplitude measures for the four major regional phases Pn, Pg, Sn and Lg. The code includes and MDAC modeling module. The code works with a database so that changes to parameters (e.g. locations, magnitudes, MDAC values, etc.) are traced and results can easily be updated to reflect the changes.

2) *Transportability* – We have been re-examining the large database of the western United States (U.S.) underground nuclear tests and earthquakes assembled under a prior agreement. This western U.S. data covers a wide range of depths and material properties and has excellent ground truth information. We define the MDAC parameters based on fitting the earthquakes alone. We are comparing and contrasting how well MDAC corrected events discriminate in the western U.S. compared to MDAC corrected events in other regions such as Eurasia. Two issues are important, first how effectively can an earthquake based MDAC model remove gross path and source effects. Second, how large is the variability in the MDAC corrected explosion source spectra from region to region. This addresses the issue of whether a particular discriminant such as high frequency P/S works everywhere or only under certain circumstances.

3) *Source Models* – The MDAC procedure uses a new generalized Brune (1970) style earthquake model to predict expected earthquake spectra. One of its parameters is the apparent stress, a ratio of seismic energy to moment. Currently the geophysical community is split on whether apparent stress is constant or increasing with the size of the earthquake. Here we briefly present some research results examining the scaling of earthquake apparent stress. Another factor in addressing the transportability is the explosion source model. We have started to investigate how effectively the existing explosion models can be plugged into MDAC using path parameters determined from earthquakes. We present some preliminary results testing some basic explosion source models on western U.S. explosions here.

OBJECTIVE(S)

Monitoring the world for potential nuclear explosions requires characterizing seismic events and discriminating between natural and man-made seismic events, such as earthquakes and mining activities, and nuclear weapons testing. We continue developing, testing, and refining size-, distance-, and location-based regional seismic amplitude corrections to facilitate the comparison of all events that are recorded at a particular seismic station. These corrections, calibrated for each station, reduce amplitude measurement scatter and improve discrimination performance. We test the methods on well-known (ground truth) datasets in the U.S. and then apply them to the uncalibrated stations in Eurasia, Africa, and other regions of interest to improve underground nuclear test monitoring capability.

RESEARCH ACCOMPLISHED

As part of the overall National Nuclear Security Administration Ground-based Nuclear Explosion Monitoring (GNEM) Research and Engineering program, we continue to pursue a comprehensive research effort to improve our capabilities to seismically characterize and discriminate underground nuclear tests from other natural and man-made sources of seismicity. To reduce the monitoring magnitude threshold, we make use of regional body and surface wave data to calibrate each seismic station. Our goals are to reduce the variance and improve the separation between earthquakes and explosion populations by accounting for the effects of propagation and differential source size.

Efficient Processing

Effective earthquake-explosion discrimination has been demonstrated in a broad variety of studies using ratios of regional amplitudes in high-frequency (primarily 1-to 20-Hz) bands (e.g. Walter et al., 1995, Taylor, 1996, Rodgers and Walter, 2002, Taylor et al., 2002 and many others). When similar-sized earthquakes and explosions are nearly co-located, we can understand the observed seismic contrasts, such as the relative P-to-S wave excitation, in terms of depth, material property, focal mechanism and source time function differences. However it is well known that path propagation effects (e.g. attenuation, blockage) and source scaling effects (e.g. corner frequency scaling with magnitude) can make earthquakes look like explosion and vice versa. We have developed techniques a technique MDAC (Magnitude and Distance Amplitude Corrections, Walter and Taylor, 2002) that can account for these effects with proper calibration. Such calibration is most effective if a very large number of earthquakes can be used.

To efficiently process larger data sets we have recently developed a database tool call RBAP (Regional Body-wave Amplitude Processor). RBAP provides a organized way to do the necessary processing, including the ability to add new events as they become available in the database, recalculate results based on new information (e.g. better location, magnitude, velocity model, MDAC parameters) and store the results for analysis or future use in the database. RBAP capability includes the users ability to select data, review traces for quality, mark arrivals, control the location of phase (and noise) windows, make amplitude measures, estimate MDAC parameters and calculate MDAC values (using coda base Mw's and database locations). The processing is organized by station centric projects controlled by authorship. The tool is quite sophisticated, providing multiple GUI interfaces, depending on a particular configuration of the database and containing more than 100,000 lines of Java and 10,000 lines of PL/SQL. It was developed over the past year with close coordination between the users and the developers and we are now working on fine-tuning it.

Given the limited space in this paper, we show just two screen shots from an RBAP project of western US earthquakes at ELK. In Figure 1 we show the initial setup window and map and in Figure 2 we show the interactive picking module for an example event. In the initial window the user can select the dataset from the database by placing restrictions on date, time, magnitude, depth, and event type. Alternatively the user can input a specific list of events as was done here. The user can also draw a polygon on the map (or import one) to select data based on geographic region. The user can also restrict the waveform retrieval to particular channels. After data selection is committed the data is retrieved and events plotted on the map and labeled by database evid (event ID). The data is then ready for analysis in the picking module.

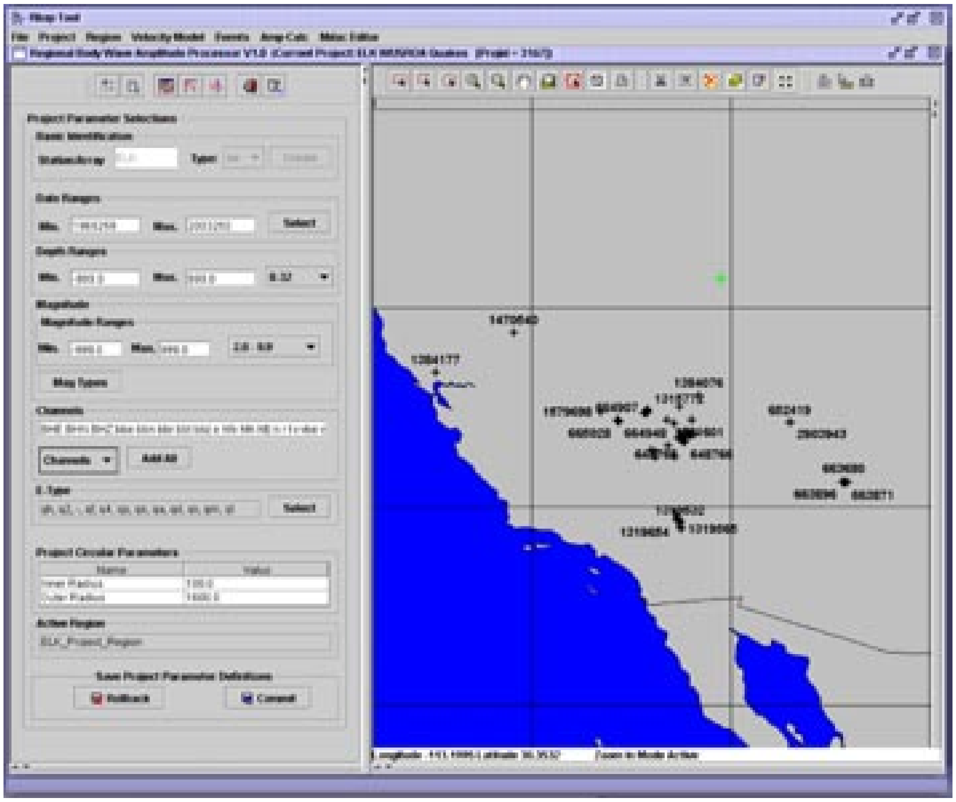

Figure 1. RBAP screen shot of initial set up window and map.

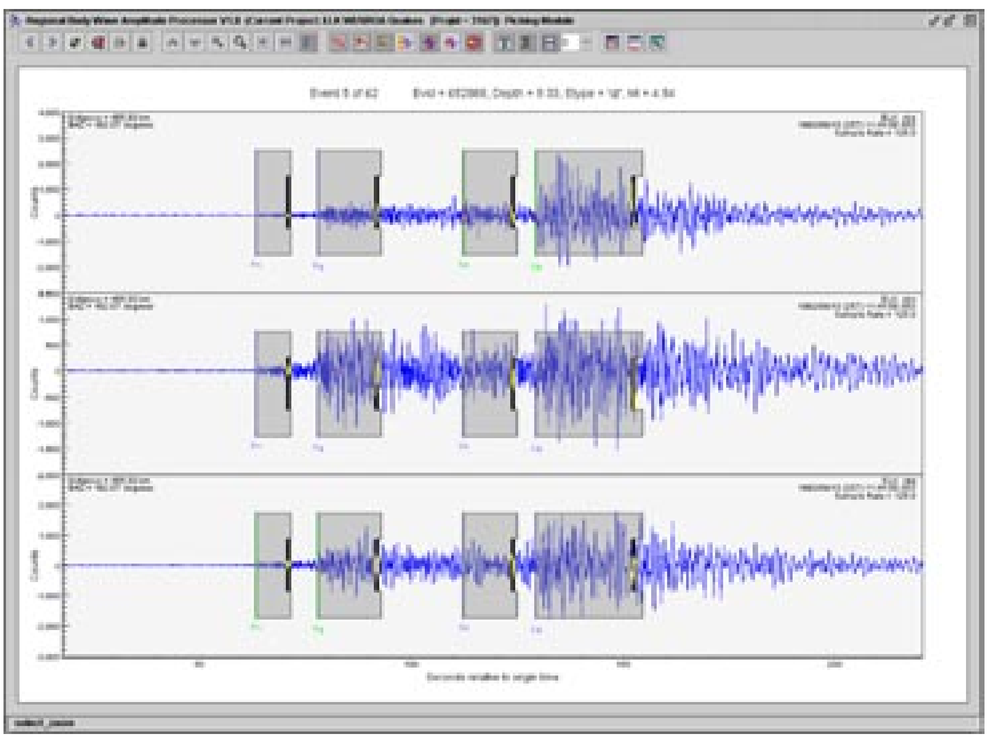

Figure 2. Screen shot of RBAP interactive picking module for an example earthquake at ELK.

Next we show an example of the interactive picking and window control portion of the tool in Figure 2. In this example of a western U.S. earthquake, part of an earthquake project at station ELK, the tool has imported LLNL analyst Flori Ryall's picks for Pn, Pg, Sn and Lg (green). If the tool user had re-picked a phase it would be labeled black (black) and the grey-blue picks are nominal based on a velocity model and automatically migrated to other components (or array elements). Window ends are also controlled by a user settable velocity model or user hand-picked times. The interactive tool allows filtering, zooming and marking of bad trace portions and is designed to allow the user to work through a data list picking arrivals and setting windows and then calculating all the amplitudes in a batch processing mode. Other parts of the tool (not shown) allow MDAC parameter determination and calculation.

Transportability

We have been re-examining the large database of the western United States (U.S.) underground nuclear tests and earthquakes assembled under a prior year BAA. This western U.S. data covers a wide range of depths and material properties and has excellent ground truth information. We define the MDAC parameters based on fitting the earthquakes alone. A longstanding problem in monitoring research is how best to transport discriminant measures to other stations in different parts of the world where we may not have any prior nuclear test data. We can illustrate some of the problems just by transporting results between stations within the western U.S. Figure 3 shows the raw and MDAC corrected measurements of 6-8 Hz Pn/Lg at stations KNB and ELK as a function of distance and magnitude. For the raw data it is clear that the mean values of the populations are different at each station. After the MDAC correction the earthquakes have similar mean values near zero (clear distance trends have been removed), but the KNB explosions have a higher values than ELK. This 6-8 Hz Pn/Lg discriminant simply works better at KNB than ELK. These stations are in the same gross tectonic region and this difference appears to be due to suble differences in propagation and energy partitioning in the regional phases. This example points to the need to do detailed calibration, station-by-station for regional discriminants. We do not believe there are any easy shortcuts to this process if true and optimal discrimination performance is to be assessed.

An additional issue for optimal discrimination is to make use of multiple discriminant measures, some of which may work only in that region. For example in Figure 4 we show three different discriminant measures that have been shown to work well in the western U.S. (e.g. Walter et al., 1995). One of them 6-8 Hz Pg/Lg does better than the other two, but still there are events that do not discriminate well. We highlight one earthquake and one explosion in the figure. Note that they discriminate better using the other two measures. Optimal combinations of measurmements can give a better overall performance than any individual measure as shown in the combined measure plot. Here we made use of a low to high frequency spectral ratio in Lg. It is well known that this discriminant does not work as well in central Asia as it does in the western U.S. (e.g. Hartse et al. 1997). However if we used only discrimiants that are highly effect globally such as high frequency P/S ratios, we would hobble our potential discrimination capability in the western U.S. and elsewhere. Again we believe that detail calibration studies to calibrate with a large set of prior earthquakes, mapping out structure using kriging (e.g. Schultz et al, 1998) and/or attenuation tomography, and determining optimal discriminant measures and their combinations can dramatically improve performance.

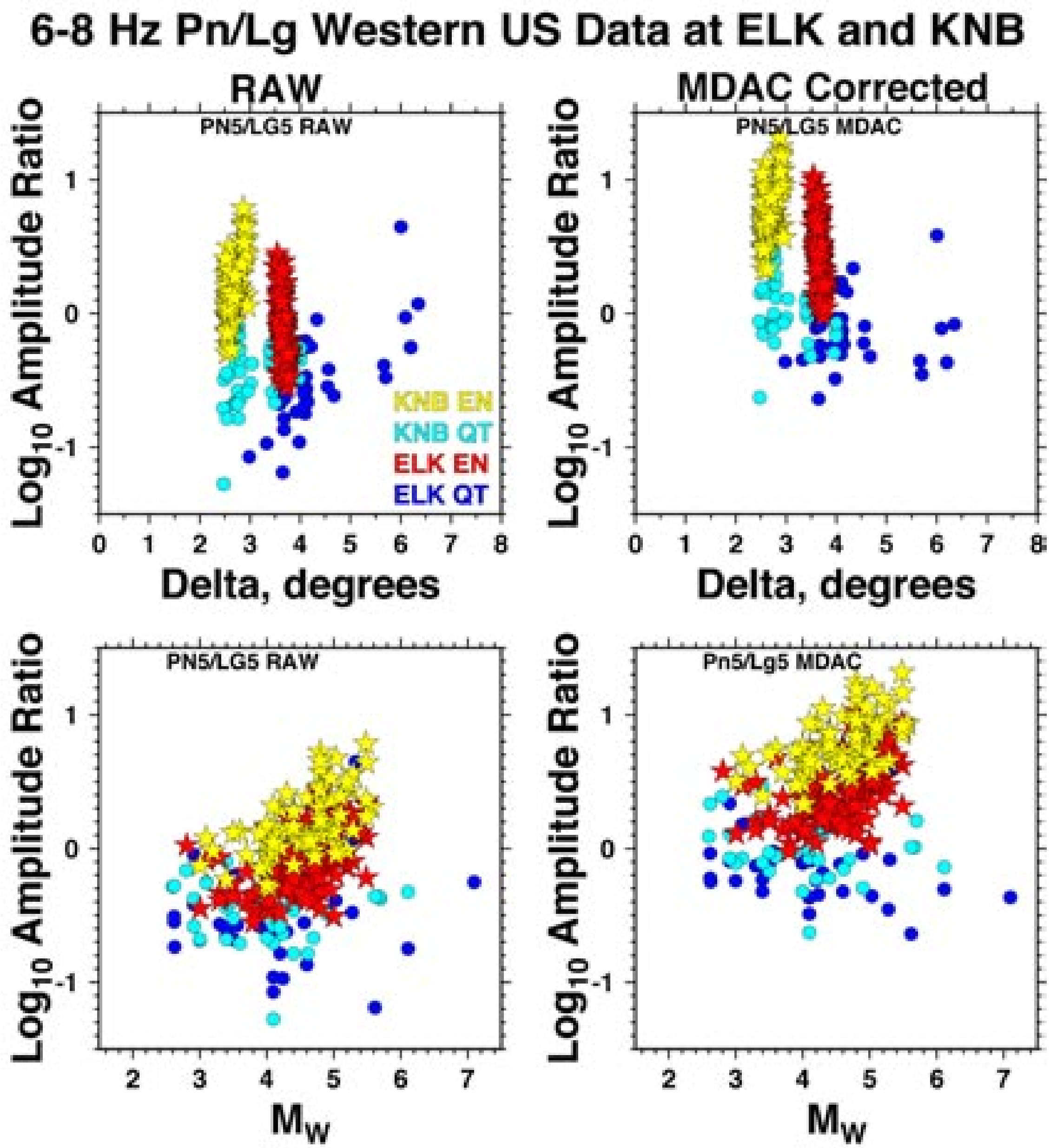

Figure 3. Western U.S earthquakes (circles) and nuclear explosions (stars) for the discriminant phase ratio 6-8 Hz (our frequency band 5) Pn/Lg at stations KNB and ELK. Left-hand side shows raw data as a function of distance (top) and magnitude (bottom). Right-hand side shows MDAC corrected data. Note that strong distance trends apparent in the raw data especially at ELK are removed by MDAC, improving discrimination. Even after MDAC correction it is clear this discriminant works better at KNB than ELK. Thus we show that transportability even between stations in the western U.S. is challenging, and there is no substitute for detailed regional calibration.

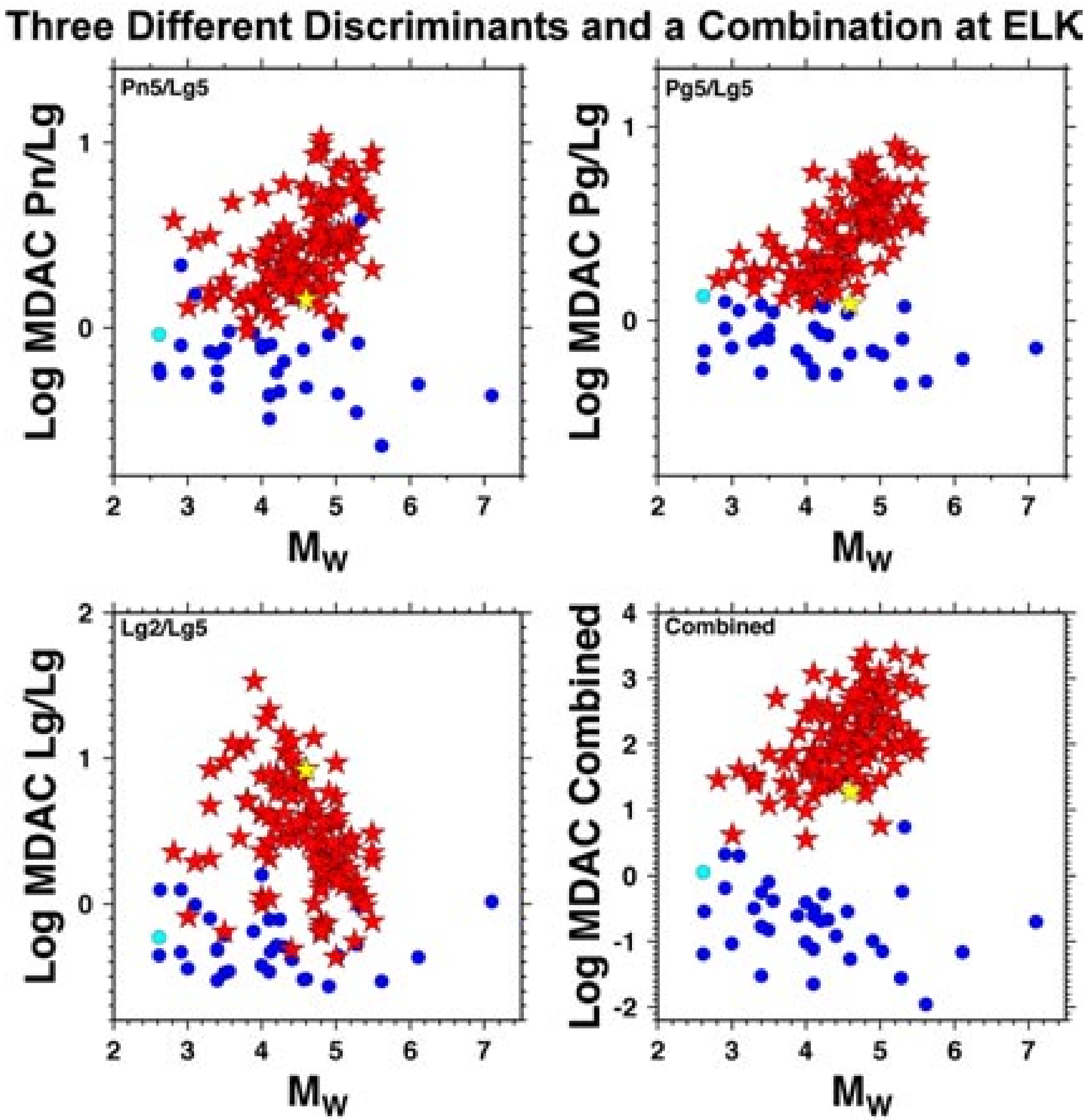

Figure 4. Examples of three different discriminant measures and an optimal combination of all of them at station ELK. The data are the same western U.S. earthquakes and nuclear tests shown in Figure 3. The measures are 6-8 Hz (our band 5) Pn/Lg, 6-8 Hz Pg/Lg and 1-2 Hz (our band 2) Lg to 6-8 Hz Lg. The data have all been MDAC corrected. The best individual discriminant for this station is 6-8 Hz Pg/Lg, but even here there is some overlap. We highlighted two events that do not discriminate well for Pg/Lg, one southern NTS earthquake on 1/19/02 and one NTS Yucca flat explosion Roquefort on 10/18/85. Note that these events discriminate better for the other measures particularly the Lg spectral ratio. Each event varies on which measure works best for them. Thus, when we combine all 3 measures we get a much better overall discrimination performance.

<u>Source Models</u>

The MDAC procedure uses a new generalized Brune (1970) style earthquake model to predict expected earthquake spectra. One of its parameters is the apparent stress, a ratio of seismic energy to moment. Currently the geophysical community is split on whether apparent stress is constant or increasing with the size of the earthquake (for example see http://earthscience.llnl.gov/scaling-workshop/). We have recently completed an LDRD funded study to look at the apparent stress scaling. In Figure 5 we shown an example using the 1999 Mw 7.1 Hector Mine mainshock and afterhocks recorded on scale at four regional stations. We integrated the energy in the Lg spectra to obtain energy and used regional coda envelope techniques to obtain moments. We show results for three different attenuation models, model A is based on Anu Venkatamaran's (written comm.) estimate of the mainshock energy, Model B is based on Jack Boatwright estimate (Boatwright et al., 2002) and Model C is based on lowering the attenuation to the point where the apparent stress scaling starts to become nearly constant. The attenuation in model C is lower than other Basin and Range studies give, which is closer to that of Model B. Although we have not resolved this issue, we have shown it is important to include the appropriate amount of apparent stress scaling for the attenuation model you are using in a region to optimally fit spectra. We do this as part of our MDAC parameter estimation process.

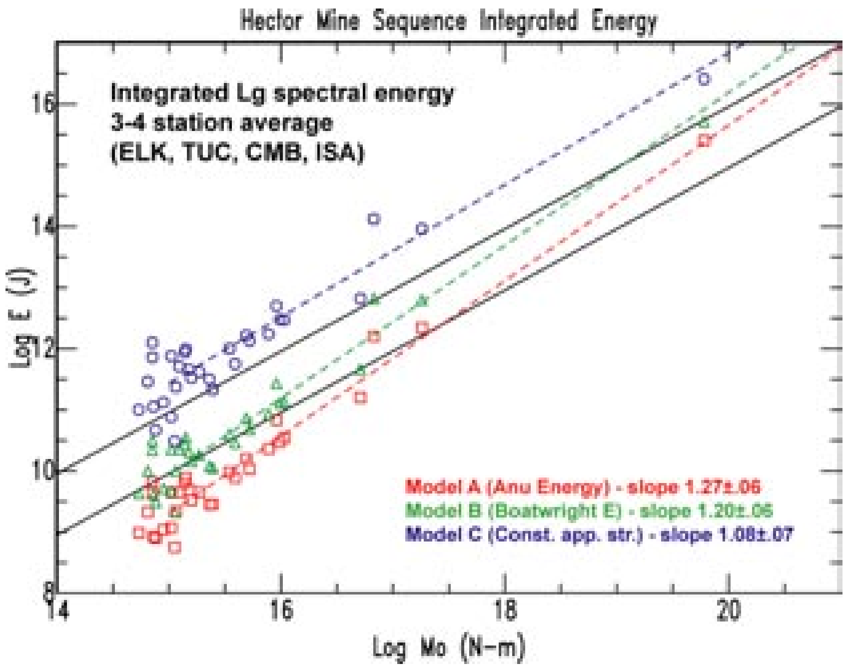

Figure 5. A plot of apparent stress scaling for the 1999 southern California Hector Mine mainshock and aftershocks for three different attenuation station specific attenuation models. These events were recorded on scale at four regional stations. Because the paths are very similar we can examine the scaling of the sequence as a whole by looking at the slope of the best fit line. Note that for typical western U.S attenuation (Model B) the data show that apparent stress increases with magnitude (slope > 1).

Another factor in addressing the transportability is the explosion source model. We have demonstrated in prior work (Walter et al., 1995) that nuclear tests at NTS in porous, gas-filled material is deficient in high frequencies compared to tests don in saturated material. We show an example in Figure 6 for two tests that have similar coda magnitudes recorded at the same station.

We have started to investigate how effectively the existing explosion models can be plugged into MDAC using path parameters determined from earthquakes. We present some preliminary results testing some basic explosion source models on western U.S. explosions in Figure 7at station ELK. The earthquake spectra are well fit by the model for all three phases out to 15 Hz. Using the same path parameters (geometrical spreading, frequency dependent attenuation) we use the Mueller-Murpy model and the announced narrow yield range to try and fit the US JVE explosion Kearsarge. The fits below 6 Hz or so are quite good but at higher frequencies the model predicts more energy than is observed. There are three possibilities, 1) the explosion model specra need to fall off faster at frequencies above about 6 Hz than the f-2 of the model and/or 2) that the attenuation model is not right (which would need to be compensated by a corresponding change in the earthquake apparent stress and/or that the path corrections are different at high frequencies for earthquakes and explosions due to the depth difference of the sources. Currently we are researching this issue. Finally there is the well known problem of the lack of a good explosion S-wave model to use in this kind of evaluation.

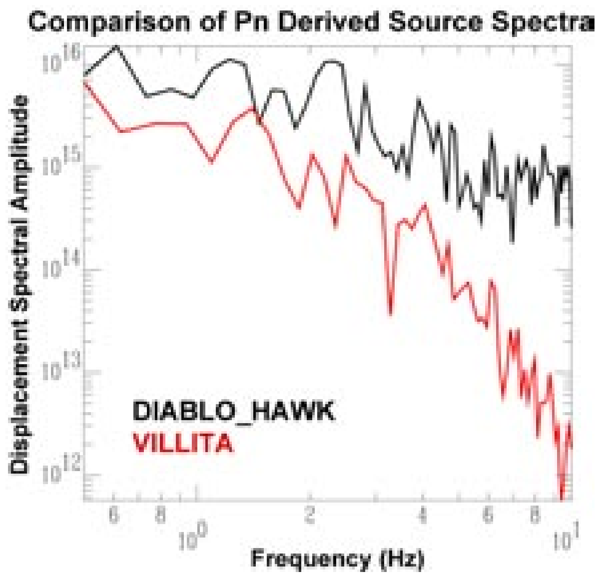

Figure 6. Comparison of path-corrected Pn spectra of two similar size (Mlcoda 4.30-4.39) and depth (373-388m) events at station KNB. DIABLO_HAWK has gas porosity of only 1.8% while VILLITA has a gas porosity of 20%. This plot clearly shows that source spectra are strongly dependent on media properties.

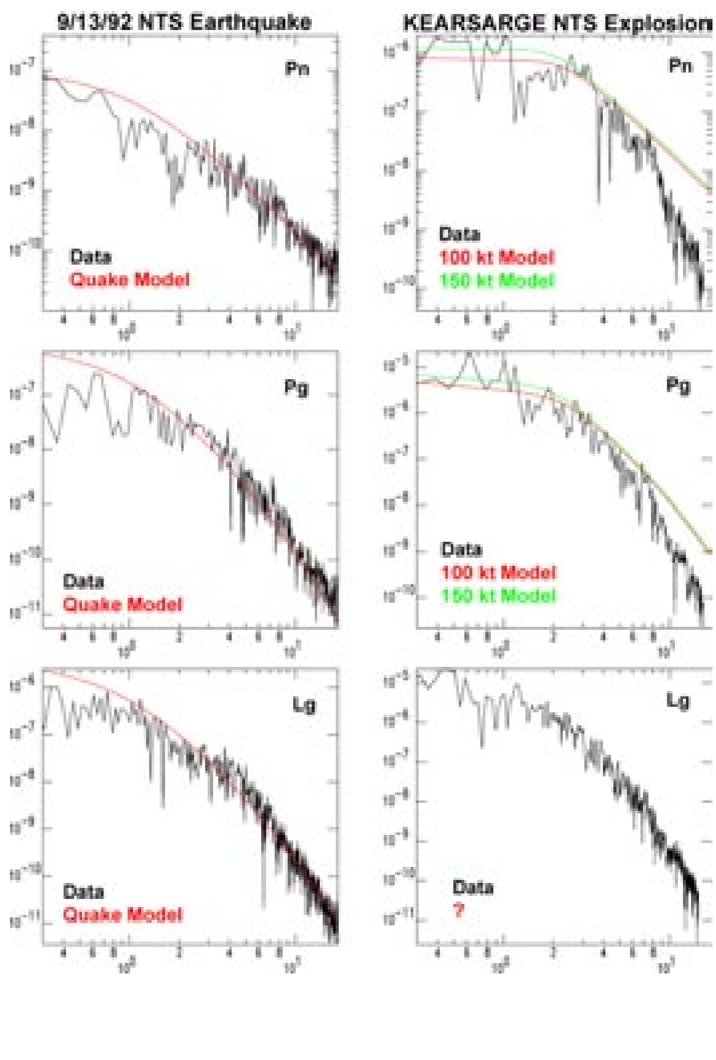

Figure 7. Regional Pn, Pg and Lg spectral fits of an NTS earthquake (left hand side) and an NTS explosion using MDAC. The data were recorded at station ELK. The earthquake model is based on Mw=4.32 and apparent stress of 0.15 Mpa from Mayeda and Walter (1996). The explosion is fit using the Mueller-Murphy (1971) tuff model with a depth and yield range of 100-150 from Springer et al. (2002). We currently lack a good theoretical explosion S-wave model to try and fit the Lg data.

CONCLUSION(S) AND RECOMMENDATION(S)

Regional discrimination algorithms require calibration at each seismic station to be used for nuclear explosion monitoring. We have developed a revised Magnitude and Distance Amplitude Correction procedure to remove source size and path effects from regional body-wave phases. This allows the comparison of any new regional events recorded at a calibrated station with all available reference data and models. This also facilitates the combination of individual measures to form multivariate discriminants that can have significantly better performance.

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